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ABSTRACT

This second in a series of eight modules for a course titled Mechanical Inspection describes typical pump functional tests which are performed after pump installation and prior to release of the plant for unrestricted power operation. The module follows a typical format that includes the following sections: (1) introduction, (2) module prerequisites, (3) objectives, (4) notes to instructor/student, (5) subject matter, (6) materials needed, (7) procedures, (8) data table, (9) reference materials, (10) test. (The course is one of fifteen technical courses for the second year of a two-year postsecondary curriculum in Nuclear Quality Assurance/Quality Control Technology.) (LRA)

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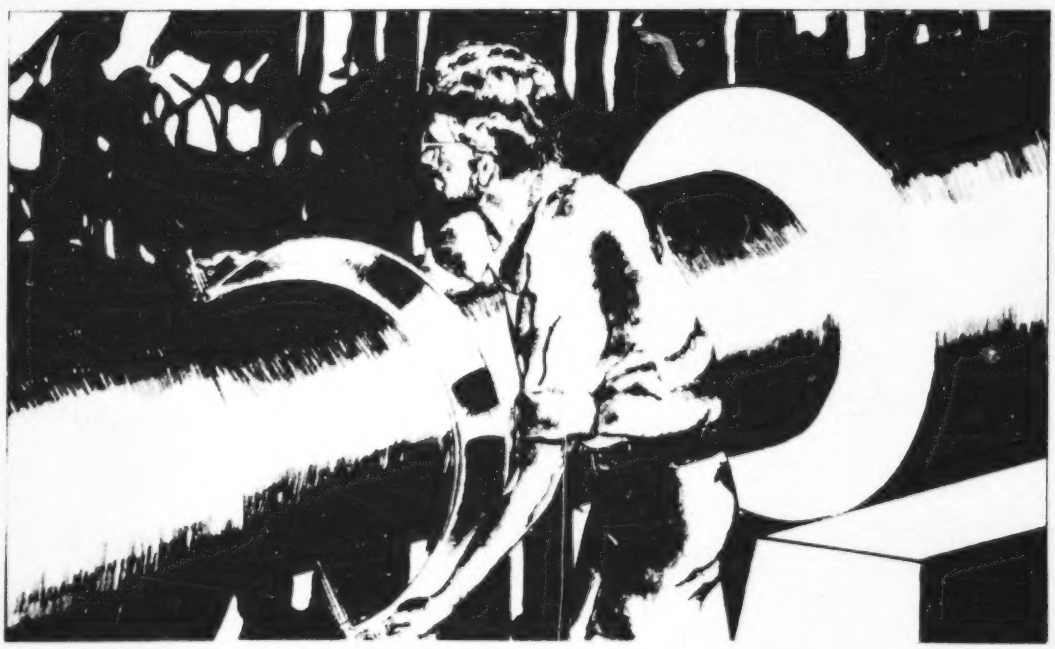
NUCLEAR TECHNOLOGY

COURSE 30 MECHANICAL INSPECTION

MODULE 30-2 Pump Functional Testing



CE 024 278

GENERAL PHYSICS CORPORATION
Columbia , Maryland

COURSE MODULES

COURSE 30 MECHANICAL INSPECTION

Module 30-1 Pump Inspection
Module 30-2 Pump Functional Testing
Module 30-3 Valve Inspection
Module 30-4 Piping Inspection
Module 30-5 Surface Cleaning Inspection
Module 30-6 Protective Coating Inspection
Module 30-7 Pressure Vessel Inspection
Module 30-8 Rotating Equipment Inspection

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This module was prepared for General Physics Corporation by Ed Wasil and John Espy, General Physics Corporation.

GENERAL PHYSICS CORPORATION

1979

INTRODUCTION

The Nuclear QA/QC Technician is intimately involved with pump functional testing. The technician witnesses key portions of tests to verify proper conduct of tests. The technician reviews test reports for completeness. And, the technician monitors testing performance to ensure use of correct procedures, calibrated test equipment, use of qualified test persons, compliance with test prerequisites, and proper acceptance of test results.

This module describes typical pump functional tests which are performed after pump installation and prior to release of the plant for unrestricted power operation. During this time interval, tests are typically classified as preoperational, cold functional, hot functional, and start-up. These phases of testing are defined and the types of pump tests in each are described.

Primary emphasis is given to specific pump functional tests. Purpose of each test is stated and methods of conducting the tests are described. Prior to presenting these specific tests, this module summarizes performance characteristics of centrifugal pumps and reciprocating pumps. This summary should assist in the understanding of the specific pump tests.

MODULE PREREQUISITES

Knowledge of types of pumps and their fundamental principles of operation and knowledge of pressure and flow detection and measurement systems are required. The student/trainee should have completed Module 31-1 of this course.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Define the terms capacity, pump head, output power, brake horsepower, and pump efficiency as they relate to centrifugal pumps.
2. Define the terms capacity, displacement, and slip as they relate to reciprocating pumps.
3. Recognize typical performance curves for centrifugal pumps and relate pump operating conditions to the curves.
4. Define cavitation and describe how it is avoided.
5. Describe the interrelationships of capacity, discharge pressure, pump speed, and discharge throttle valve settings for a reciprocating positive displacement pump.
6. State the purpose of and briefly describe how to conduct any of the following individual pump tests:
   a. direction of rotation
   b. vibration
   c. motor load versus time
   d. seal leakage
   e. seal cooling
   f. flow and pressure characteristics
   g. acceleration
   h. coastdown
7. State the purpose of and briefly describe how to conduct the following types of pump systems tests:
   a. start-stop functions
   b. variable speed functions
8. Briefly describe the type of information provided by pump functional test procedures in any of the following sections of the procedure:
   a. title, number, and revision
   b. test objectives
   c. test equipment

d. limitations
e. prerequisites
f. procedure, notes, and cautions
g. acceptance criteria

CENTRIFUGAL PUMP CHARACTERISTICS

Definitions

Principle terms associated with the operating characteristics of centrifugal pumps are pump capacity, pump head, output power, brake horsepower, and pump efficiency. Definitions of these terms and their symbols are:

- Pump capacity - The volume of fluid per unit time delivered by the pump. Capacity is represented by the symbol Q and is expressed in gallons per minute (gpm) or cubic feet per second (ft^3/sec).
- Pump head - The net work done on a unit weight of fluid in passing from the suction to the discharge. Head is represented by the symbol H and is expressed in units of feet.
- Output Power - The liquid horsepower delivered by the pump to the fluid. Output power is expressed as liquid horsepower and symbolized by lhp.
- Brake horsepower - the horsepower delivered by the prime mover to the pump shaft. Brake horsepower is symbolized by bhp.
- Pump efficiency - The ratio of output power to input power, re, the ratio of liquid horsepower to brake horsepower. It is expressed as percentage and symbolized by η.

Head Versus Capacity

The centrifugal pump adds kinetic energy to the fluid by the rotation of the pump impeller. A portion of the kinetic energy is converted to pressure in the volute. In order to introduce the relationship between head and capacity, a simplified description of these effects is presented using the pump illustrated in Figure 30-2-1.

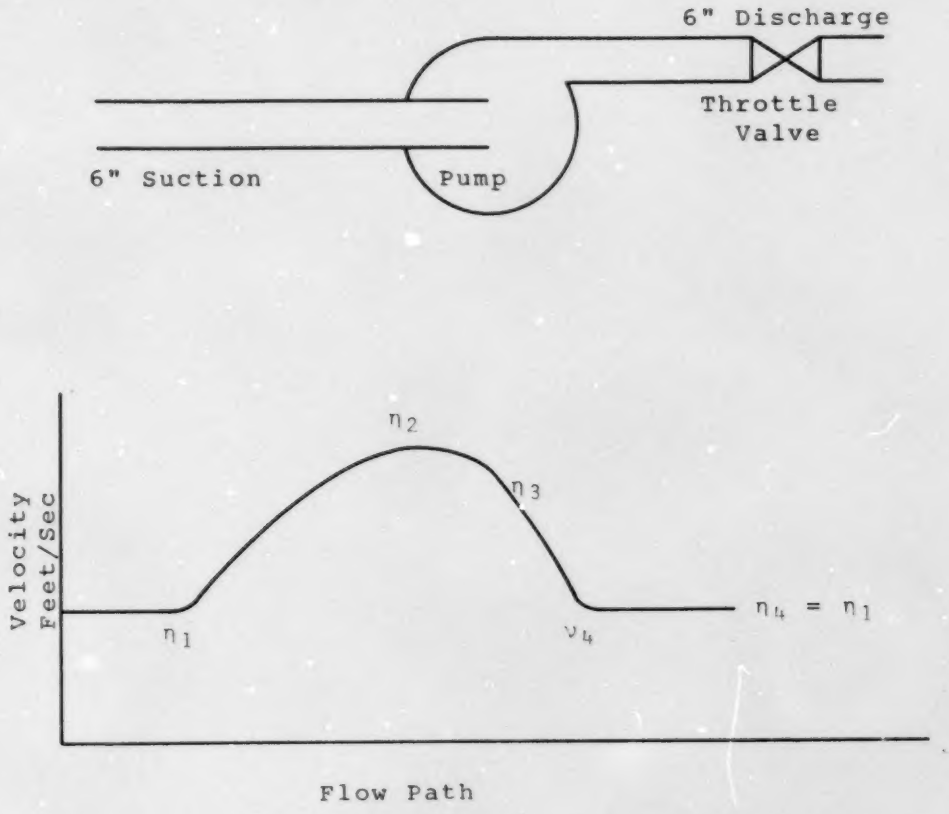

Figure 30-2-1. Velocity through a Centrifugal Pump

As illustrated in Figure 30-2-1, the suction and discharge piping in this example are of equal size. With the pump running and the throttle valve open, it is logical that the fluid flow into the pump equals the fluid flow out of the pump. With equal pipe sizes, velocity v_1 equals velocity v_4. The point of highest velocity is at the outer tip of the impeller and is designated v_2. Velocity v_3 is somewhere in the volute. The decay of velocity from v_2 to v_4 is accompanied by a pressure rise proportional to the decrease in velocity squared.

Picture what happens when the throttle valve is shut with the pump still running. Velocities v_1 and v_4 go to zero but velocity v_2 theoretically exists. The impeller is imparting kinetic energy to the fluid but with the

throttle valve closed, all of the kinetic energy is converted to pressure. This condition produces maximum discharge pressure. It is termed shutoff head.

As the throttle valve in Figure 30-2-1 is slowly opened, velocities v_1 and v_4 rise. This means that not all the kinetic energy added by the impeller is converted to pressure. Instead, some kinetic energy remains as the velocity head. It is logical that the pressure head is now less than the shutoff head.

The actual relationship between pump head and capacity is much more complicated. It should be recalled that pump head is comprized of pressure head, velocity head, and elevation head. Variables affecting pump head versus capacity include number of vanes in the impeller, thickness and curvature of the vanes, and volute design. The actual performance factors are so complicated that specific tests are conducted for each pump design to determine the performance characteristics for that design. The test results are plotted to yield an accurate performance chart such as the one illustrated in Figure 30-2-2.

Referring to Figure 30-2-2, pump head decreases as capacity increases. Efficiency increases to a maximum and then decreases as capacity increases. These relationships hold generally true for all designs of centrifugal pumps.

Pumps are designed to operate at the point of best efficiency. If the system design required 5000 gpm pump capacity at a pump head of 2800 feet, the pump represented by Figure 30-2-2 would be a suitable pump. This is because maximum efficiency for that pump occurs at about 5000 gpm and 2800 feet. However, if the system required a substantially different capacity or pump head, another pump design would be selected which would operate at best efficiency at the designated capacity and pump head.

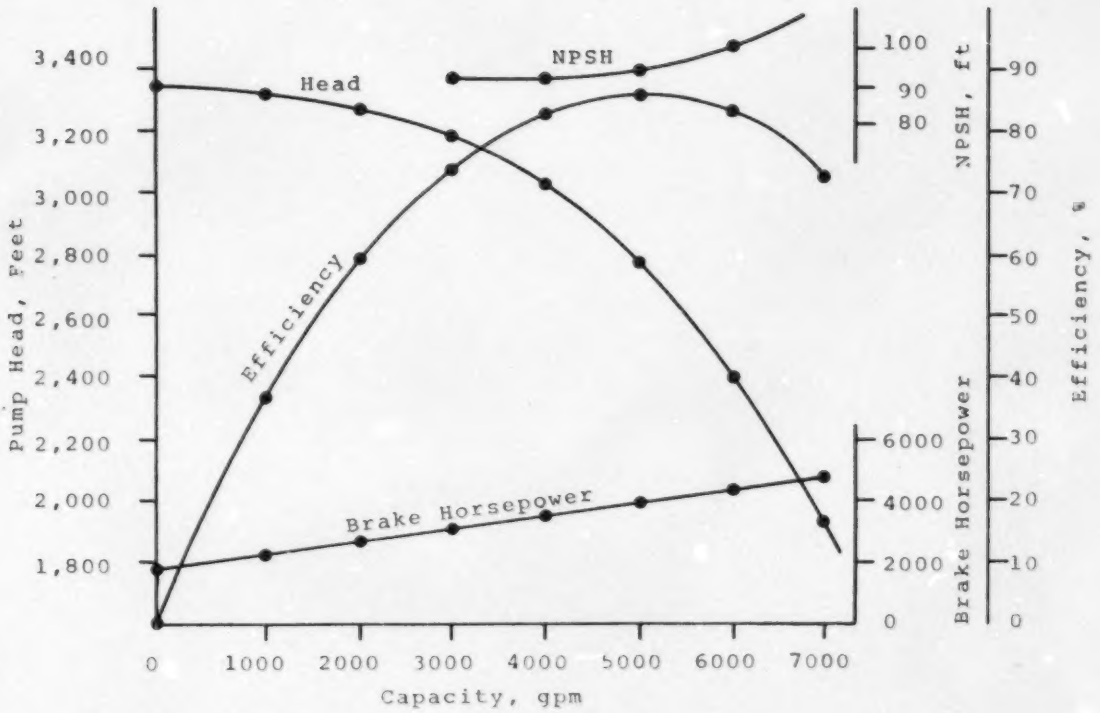

Figure 30-2-2. Example Performance Curves for Multi-Stage Centrifugal Pump

Net Positive Suction Head

Net Positive Suction Head (NPSH) is a term referring to the absolute pressure of the fluid at the lowest point of pressure in an operating pump. In a centrifugal pump, the point of lowest pressure is normally near the outer tip of the impeller vanes. At such a point, too low an absolute pressure permits portions of the fluid to vaporize and form gas bubbles. These bubbles collapse as they are forced into a larger pressure area. Such formation and collapse of bubbles is termed cavitation.

Cavitation in centrifugal pumps gives serious problems and is avoided. Cavitation causes reduced capacity, accelerated errosion of impeller vanes, and increased pump vibra-

tion.

The actual pressure at which cavitation occurs is dependent on several factors including pump design and the vapor pressure of the fluid. The minimum pressure necessary to prevent cavitation is designated by the pump manufacturer as required net positive suction head (RNPSH). The actual dynamic suction head provided in the operating system is the available net positive suction head (ANPSH). Cavitation does not occur as long as ANPSH is equal to or greater than RNPSH.

RECIPROCATING PUMP CHARACTERISTICS

Definitions

Principle terms associated with characteristics of positive displacement reciprocating pumps are capacity, displacement, pressure, brake horsepower, slip and speed. Definitions of these terms are:

- Capacity - The total volume of fluid delivered per unit time. Capacity is expressed in units of gallons per minute (gpm) and symbolized by Q.
- Displacement - The calculated capacity of the pump in gpm and symbolized by D.
- Pressure - The differential pressure from discharge to suction. It is noted that because discharge pressure is typically so much larger than suction pressure in systems using reciprocating pumps that discharge pressure alone is typically of concern. Pressure is symbolized by P.
- Brake horsepower - The horsepower delivered by the prime mover to the pump crankshaft. It is symbolized by bhp.
- Slip - The capacity loss as a percentage of suction capacity. Slip is expressed as a percentage and is

symbolized by S.

- Speed - The revolutions of the crankshaft per unit time speed is expressed in revolutions per minute (rpm) and symbolized by n.

Capacity Versus Head

Capacity of a reciprocating positive displacement pump is a function of speed, number of pistons, piston size, and stroke length. Theoretically, capacity equals displacement but in reality slip occurs such that capacity is less than displacement. Capacity is calculated by the formula:

$Q = D(1-S)$ Formula 30-2-1

where

Q = Capacity in gpm
D = Displacement in gpm
S = Slip expressed as a decimal fraction (expressed as per unit)

Slip occurs from three sources: fluid compressibility, leakage past the piston, and reverse fluid flow through valves when valves are closing or seated. Fluid compressibility is of little consequence when pumping liquids except at very high discharge pressures. Leakage past pistons is normally very low. The largest component of slip by far is the reverse flow through valves. Slip values may range from 5 to over 30% dependent upon the fluid pumped, viscosity of the fluid, speed of the pump, and other variables.

Pump displacement is the calculated capacity of its pump assuming no slip. For single-acting reciprocating pumps, displacement is calculated by the formula:

$$D = \frac{A \times m \times n \times s}{231}$$ Formula 30-2-2

where:

D = Displacement in gpm

A = Cross-sectional area of piston in square inches

m = Number of pistons

n = Speed of pump in rpm

s = Stroke of pump in inches

For double-acting reciprocating pumps, displacement is calculated by the formula:

$$D = \frac{(2A-a)m \times n \times s}{231}$$ Formula 30-2-3

where:

D = Displacement in gpm

A = Piston cross-sectional area in in^2

a - Piston rod cross-sectional area in in^2

m = Number of pistons

n = Speed in rpm

s = Stroke in inches

For purposes of describing the interrelationship between capacity and pump head, the illustration of Figure 30-2-3 is used.

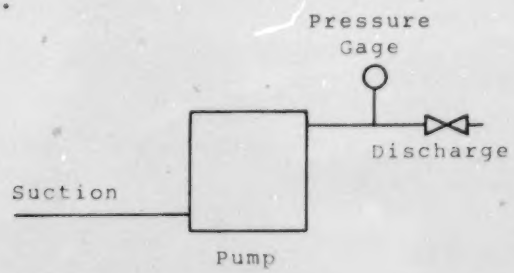

Figure 30-2-3. Simplified Sketch of Reciprocating Pump

Referring to Figure 30-2-3, let us assume that the pump

is running at constant speed, the discharge valve is fully open, and the fluid is discharging to the atmosphere. With these conditions, the pressure gage reads zero if friction is disregarded. The capacity is probably about 90% or more of displacement because slip is least when discharge pressure is lowest. Now picture what happens as the discharge valve is closed. At some point of closing, the valve permits discharge flow exactly equal to pump capacity. If valve closure is increased slightly beyond this point, discharge flow tends to become less than suction flow. Nonetheless, its pump is moving essentially the same volume of fluid with each revolution. The result is a rapid increase in discharge pressure until the increased pressure causes flow through the valve equal to pump capacity. At such a valve setting. pressure stabilizes at some value and discharge flow equals suction flow. Further closure of the valve results in another increase in pressure until discharge flow equals pump capacity. If its discharge valve is fully closed, pressure theoretically increases to infinity. In reality, some point in the system would rupture if the valve were closed with the pump running. To avoid this, safety relief valves are provided either integral with the pump or in the discharge piping before the first isolation valve.

In the foregoing discussion, slip was ignored. In reality, slip increases somewhat as discharge pressure increases. However, such increased slip is minimal and the rapid rise in discharge pressure with closing of the discharge valve always occurs. Therefore, it is concluded that with constant speed, capacity of the reciprocating pump is fixed by the pump design and that discharge pressure is equal to the pressure of the system receiving the discharge.

Effect of Speed

Speed of a reciprocating pump directly affects displacement and slip. As speed increases, displacement increases proportionately as indicated by Formula 30-2-3. Slip also increases as pump speed increases. Therefore, the increase in capacity is somewhat less than the increase in displacement by an amount determined by the increase in slip. The specific relationship is determined by tests conducted by the pump manufacturer and provide performance curves for the pump.

Net Positive Suction Head

The required net positive suction head (RNPSH) for reciprocating pumps is that head necessary to maintain fluid in contact with the piston during the intake stroke. The valve of RNPSH is dependent on piston size, pump speed, pump capacity, and pressure.

A large component of RNPSH is the acceleration head. Fluid flow in the suction line is constantly accelerating and decelerating with intake and discharge strokes of the pump. The head necessary to support the acceleration of fluid in the suction line is the acceleration head. It is calculated by the formula:

$$H_a = \frac{L \times V \times n \times c}{g \times k}$$ Formula 30-2-4

where:

H_a = Acceleration head in feet

L = Length of suction pipe in feet

V = Mean velocity in the suction pipe in feet per second.

$$V = \frac{gpm \times .321}{\text{area of pipe, in}^2}$$

n = Speed of the pump in rpm

C = Function of the number of pistons

Duplex = 0.115

Triplex = 0.06

Quadraplex = .08

Quintuplex = .04

Sextuplex = .055

Septuplex = .028

g = Acceleration of gravity, 32.2 ft/sec^2

K = Factors for various fluids

Water = 1.4

Oil = 2.5

FUNCTIONAL TESTS OF PUMPS

Purpose

Functional testing of pumps serve two primary purposes. First, tests of the pump as an individual component demonstrate that the pump itself functions as designed. Secondly, tests of systems which use the pump demonstrate that the system functions as designed. The Nuclear Regulatory Commission requires that both individual pump tests and system tests be conducted after completion of installation whenever the system serves a safety related function. The owner also tests pumps in non-safety related systems to verify readiness to commence plant operations.

Systems Using Pumps

Most all piping systems in a nuclear power plant use pumps. Typical systems which use pumps in pressurized water reactors are listed in Table 30-2-1. Typical systems which use pumps in boiling water reactors are listed in Table 30-2-2.

Pump name	Number per plant	Flow, gpm	Head, ft	Design pressure, lb/in²		Driver, hp		Speed (nominal), rpm	Notes
Reactor coolant	4	93,000	305	2,500		8,000		1,200	
Component cooling water	2	4,800	250	250		500		1,800	
Residual heat removal	2	3,000	270	600		400		1,800	
Containment spray	2	2,600	450	300		400		1,800	
Spent-fuel pit	2	2,300	125	250		100		1,800	
Charging (centrifugal)	2	650	3,000	2,800		900		4,550	Gear drive
Safety injection	2	425	2,500	2,500		400		3,600	
Chilled water	2	400	150	150		40		3,600	
Spent-resin sluicing	1	140	250	150		25		3,600	Canned
Spent-fuel pit skimmer	2	100	50	150		5		3,600	
Reactor-coolant drain tank	2	100	300	150		20		3,600	Canned
Charging (positive displacement)	1	98	5,800	3,200		200		50/250	Variable speed
Boric acid transfer	4	75	235	150		15		3,600	Canned
Floor drain tank	1	35	250	150		15		3,600	
Recycle evaporator feed	2	30	320	150		20		3,600	Canned
Boron injection recirculation	2	20	100	150		5		3,600	Canned

Table 30-2-1.
Typical Pumps in Pressurized Water Reactor

Pump name	Number per plant	Flow, gpm	Head, ft	Design pressure, lb/in²		Driver, hp			Speed (nominal), rpm	Notes
Recirculating coolant	2	35,400	865	1,675		7,200			1,800	
RHR service water	4	7,300	115	150		300			900	
Residual heat removal	3	7,100	275	450		900			1,800	
High-pressure core spray	1	6,110	900	1,600		3,000			1,800	
Low-pressure core spray	1	6,110	730	550		1,750			1,800	
Closed cooling water	3	1,700	110	250		60			1,800	
Reactor-core isolation cooling	1	725	2,800	1,500		800			4,000	Turbine-driven-variable speed
Fuel-pool cooling	2	600	300	150		75			1,800	
Reactor-water cleanup	2	150	500	1,400		50			3,600	
Control rod drive hydraulic system	2	95	3,500	1,750		300			1,800	
Standby liquid control	2	40	2,800	1,400		40			1,800	Reciprocating pumps

Table 30-2-2.

Typical Pumps in Boiling Water Reactor

Functional Design Features

The decision on what tests will be conducted is based on "what are the functional design features?" If all functions of the pump and system are known, it is relatively easy to establish a series of tests which will determine that such functions are served by the pump and system. The key for assuring that all necessary tests will be conducted is whether a test objective exists for each functional design feature. If there is a match between test objectives and all functional design features, adequate test plans have been developed.

Plant Operational Status

Functional testing is performed during the time interval between installation and power operation. These tests are subdivided into four categories: preoperational tests, cold functional tests, hot functional tests, and start-up tests. Assignment of specific tests of pumps to any of these categories involves engineering judgment to some extent and, consequently, absolute categorizations of pump tests is not attempted herein. The purpose of each category of tests and example pump tests within each are as

follows:

- Preoperational tests - These tests assure that components, partial systems, or systems operate in accordance with design criteria. These tests are performed after installation and prior to fuel load. They include hydrostatic testing and individual pump tests.
- Cold functional tests - These tests obtain operational data of equipment and verify system functional performance. These tests are performed after preoperational testing and prior to fuel load. They include certain individual pump tests and pump system tests.
- Hot functional tests - These tests apply only to pressurized water reactors and are performed prior to fuel load. They essentially repeat cold functional tests with the system at elevated temperature and pressure. These tests verify the functional performance of systems at operating and design temperatures and pressures.
- Startup tests - These tests are conducted after fuel load. They verify that reactor operation complies with design requirements under normal and transient operating conditions. Pump tests are not included per se. Instead, startup tests include the observation of the proper functioning of pumps under the various operational modes.

Individual Pump Tests

Individual pump tests verify that pump functional design features are met. Certain individual pump tests are performed by the pump manufacturer. Such tests are not repeated at the installation site except as necessary to confirm that the pump properly functions as installed.

Typical tests of individual pumps after installation include:

- Direction of rotation
- Vibration
- Motor load versus time
- Seal leakage
- Seal cooling
- Flow and pressure characteristics
- Acceleration and coastdown.

Direction of Rotation Tests

Centrifugal pumps will function if direction of rotation is incorrect but at a less capacity and with risk of damage. If rotation of a gear pump is reversed, the fluid is pumped backwards, i.e., from discharge to suction. Oftentimes, the reciprocating and rotary pumps have gear boxes between the prime mover and the pump which will operate only in one direction. Attempts ar reverse direction has high potential for damaging the gears. Therefore, it is important that the installation of the prime mover result in correct rotation of the pump.

Direction of rotation tests are performed with the prime mover disconnected from the pump shaft. In this manner, damage should not result in the event direction of rotation is incorrect. Power is momentarily applied to the prime mover and the direction of rotation of its drive shaft is visually observed. The observed direction of rotation is compared with the required direction of rotation as specified in the pump specification or installation drawing. Incorrect rotation indicates improper power connections to the prime mover.

Vibration Tests

Pump manufacturers typically balance the shafts of the pump and prime mover prior to shipment. However, installation

mounts and couplings may be off line or of sufficient flexure to permit excessive vibration. Also, fluid flow with the pump running may induce vibrations in the suction or discharge piping. Cavitation is typically audibly heard before it has much effect on vibrations. Gross cavitation causes noticeable vibration. Therefore, the vibration test primarily determines the adequacy of alignment mounts, and pipe hangers at installation with respect to preventing vibration.

Vibration tests involve running the pump with fluid flow and observing vibration. In most cases, visual and touch observation of vibration is sufficient because the acceptance criteria typically requires smooth, normal running for the given type of pump. Accelerometers attached to the pump provide for a much more sensive vibration test. Some utilities use accelerometers for testing critical pumps in order to determine when corrective maintenance is necessary. In such cases, the initial test after installation serves as a "base line" against which all subsequent tests are compared.

Excessive vibration detected or initial testing typically indicates a problem with the installation rather than the pump itself. Sources of vibration include misalignment between prime mover and pump, "soft" mounts, and too few hangers to stiffly support the suction or discharge piping. However, cavitation may also be the culprit.

Motor Load Versus Time Tests

Motor load versus time tests verify the ability of the motor to satisfactorily operate the pump for sustained time periods. Typically, the motors of motor driven pumps are designed for continuous duty at rated pump capacity or higher without exceeding power and temperature limits.

This capability is tested by the motor load versus time test.

This test is performed by running the motor driven pump at the pump's rated capacity and head for a specified time such as one or two hours. Current to the motor is monitored to verify that current drawn under full load conditions does not exceed limits. Stator and bearing temperatures are monitored to confirm that these temperatures do not exceed limits under full load conditions. Also, this test may include measurement of starting currents with the aid of chart recorders connected to ammeters.

Seal Leakage Tests

Pump shaft seals are either mechanical seals or compressible packing seals. Both types of seals require small amounts of leakage for cooling. Leakage along the pump shaft, a percentage of pump discharge, or a separate water supply provides seal cooling. In all three types, leakage occurs to the atmospheric side of the seal. The amount of leakage is indicative of the condition of mechanical seals and the proper compression of compressible seals.

Seal leakage tests are conducted with the pump running at normal head and with seal cooling water supplied. The leakage is collected for a timed interval in a graduated container. The volume collected divided by the time of collection equals the leak rate. Excessive leakage is indicative of poor seals while insufficient leakage is indicative of excess sealing which may lead to overheating.

Seal Coding Tests

Seal coding tests confirm that seal temperatures are maintained within specified limits with the pump operating at full load and with the normal cooling system in service. While this test may be stipulated by engineering for any

pump, it applies mainly to pumps having a separate supply of seal cooling water. Normally, engineering specifies acceptance criteria for this test in terms of temperature rise of the cooling water. With a known flow of cooling water, the temperature rise of the water is directly dependent on the temperature of the seal. Engineering calculates the maximum temperature rise which is expected if the seal were at its temperature limit. As long as actual temperature rise remains below the maximum calculated value, the seal temperature must be below its limit.

Another method of specifying limits involves calculation of temperature at the surface of the seal housing. Engineering calculates the surface temperature which occurs if the seal temperature is at its limit. As long as actual seal housing temperature is below the calculated value, seal temperature is also below its limit.

Seal cooling tests using the temperature rise limits measure the inlet and outlet temperatures of the cooling water. The difference between these temperatures in compared with the limit. Tests using seal housing temperature limits, measure housing temperature with a contact temperature measuring device, e.g., contact thermometer or thermocouple. The measured value is compared directly with the limit.

Flow and Pressure Characteristics Tests

These tests verify that the pump functions as designed when the pump is operated in the system containing the pump. The specific test used is dependent on the type of pump being tested.

Tests of centrifugal pumps require measurement of discharge pressure and discharge flow. A typical test configuration is illustrated in Figure 30-2-5. Actual connection points for the pressure gage and flow meters must be in a length of straight pipe sufficiently downstream of elbows

to permit sensing laminar flow. Sometimes, flow straightening vanes are necessary to provide for laminar flow at the sensors.

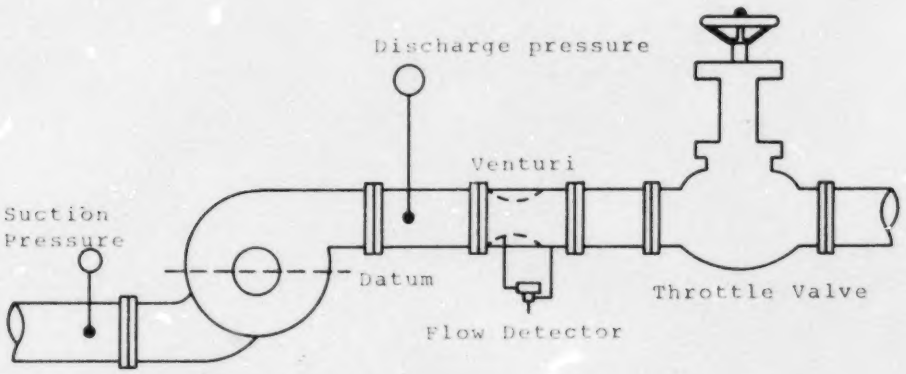

Figure 30-2-5. Example Pressure and Flow Testing

Pump head of centrifugal pumps equals the algebraic difference between total discharge head and total suction head. Pump head is therefore expressed by the formula:

$$H = H_d - H_s \qquad \text{Formula 30-2-5}$$

where:

H = Pump head in feet
H_d = Total discharge head
H_s = Total suction head

Total discharge and total suction heads are comprized of pressure head, velocity head, and elevation head. Pressure head is determined by converting measured pressure in lb/in^2 to feet by formula 30-2-5. As described later, pressure gage readings sometimes require correction to account for that vertical distance from the datum.

$$H_p = P \times \frac{144}{w}$$ Formula 30-2-6.

where:

H_p = Pressure head in feet
P = Gage pressure in lb/in^2
w = Specific weight of fluid in lb/ft^3

Velocity head is determined from flow measurements. Because most flow measuring systems indicate flow in units of gallons per minute (gpm) or cubic feet per second (ft^3/sec), conversion to feet per second is necessary to obtain velocity units. Flow in gpm multiplied by 2.228×10^{-3} equals flow in ft^3/sec. Flow in ft^3/sec divided by the cross-sectional area of the pipe in ft^2 equals velocity in ft/sec. Once velocity in ft/sec is known, velocity head is calculated by:

$$H_v = \frac{V^2}{2g}$$ Formula 30-2-7.

where:

H_v = Velocity head in feet

V^2 = Velocity of fluid in ft/sec
g - Gravitational acceleration, 32.174 ft/sec^2

Elevation head of a fluid is the vertical distance in feet above or below a reference datum. With the pump centerline as the datum, the discharge elevation head is the vertical distance from the datum to the highest point in the discharge system. The pump must add energy to the fluid to raise it to such level. The suction elevation head is the vertical distance from the level of supply fluid to the datum. In a closed loop system, it is the vertical distance from the lowest point in the system to the datum. Suction

elevation is positive when the supply level is above the datum and negative when it is below the datum.

An elevation head also exists with respect to the suction and discharge pressure gages whenever the gages are at an elevation different from the datum. In such cases the pressure indicated by the gage is corrected prior to calculating pressure head. The vertical distance between the pressure gage and the datum is measured in feet. This value is divided by 2.307 to obtain the gage elevation head in lb/in^2. The value of lb/in^2 is subtracted from gage reading when the gage is below the datum and added to gage reading when the gage is above the datum.

Adding the values of pressure head, velocity head, and elevation head yields total head of either suction or discharge. Substituting terms for these heads for H_d and H_s in formula 30-2-5 yields:

$$H = \left(\frac{Pd \times 144}{w} + \frac{Vd^2}{2g} + Z_d \right) - \left(\frac{P_s \times 144}{w} + \frac{V_s^2}{2g} + Z_s \right)$$

where: Formula 30-2-8

H = pump head, ft

$\frac{Pd \times 144}{w}$ = discharge pressure head (corrected for gage elevation)

$\frac{Vd^2}{2g}$ = discharge velocity head

Zd = discharge elevation head

$\frac{Ps \times 144}{w}$ = suction pressure head (corrected for gage elevation)

$\frac{Vs^2}{2g}$ = suction velocity head

Z_s = suction elevation head

Examination of formula 30-2-8 reveals that if dis-

charge velocity equals suction velocity, the velocity heads subtract to zero. The discharge flow of centrifugal pumps is so much larger than seal leakage flow that it can be assumed that discharge flow equals suction flow. If discharge and suction piping is of the same internal cross-sectional area, it follows that discharge velocity equals suction velocity. Therefore, the velocity head becomes important when different pipe sizes exist between suction and discharge.

Referring to Figure 30-2-5, various combinations of discharge pressure and flow are obtained by various settings of the discharge throttle valve. Tests of constant speed centrifugal pump involve determination of pump head at various capacities and comparing the results with the pump performance curves furnished by its pump manufacturer. For variable speed centrifugal pumps, the throttle valve is left fully open and the speed of the pump is varied. Total head and flow at various speeds is compared with the supplier's pump performance curves.

Tests of jet pumps verify either flow or suction pressure dependent on the function of the pump. For jet pumps used as evacuators, the absolute pressure of the evacuated space is measured and compared with specified values. For jet pumps used as eductors to provide a desired flow rate, the discharge flow rate is measured and compared with specified values.

Tests of positive displacement pumps verify capacity at design discharge pressure. Flow meters installed in the discharge line may be used or volume pumped in a timed interval , may be measured. In the latter method, the volume pumped may be measured on the discharge side or the suction side. For measurement on the discharge side, a hose is connected downstream of the pump and between two valves. The valve farthest downstream is closed such that the entire

pump discharge goes into the hose. The upstream valve is throttled to obtain discharge pressure equal to design pressure. At that throttle setting, the pump discharge is collected in a drum for a timed interval. The amount collected divided by the collection time equals pump capacity. Some positive displacement pump systems have a supply reservoir which permits calculating capacity. The hose connection and throttle valve is established as before. The amount by which the supply reservoir decreases during the timed pumping interval is used to calculate capacity.

Acceleration and Coastdown

Electrical motors, which serve as centrifugal pump prime movers, must develop sufficient torque to bring the pump up to operating speed within a designated time frame. The current drawn by the motor peaks at the instant power is applied and decays to normal operating current when the speed reaches operating speed. If too much time elapses, the excess current can damage the motor windings and insulation. Engineering calculates time for acceleration by formula 30-2-9.

$$t = \frac{wk^2 \times \Delta rpm}{308T} \qquad \text{Formula 30-2-9}$$

where:

t = time, sec

wk^2 = total moment of inertia, lb-ft^2

T = torque, lb - ft

Acceleration tests of centrifugal pumps measure the time from initial start to full operating speed. One method of measurement uses chart recorders for plotting current versus time. Another method clocks the time for speed to reach operational speed using a stop watch and a

tachometer. The first method is typically more accurate.

Acceleration tests serve two primary purposes. First, the test verifies that the motor is capable of starting the pump under system operating conditions without damage to the motor. Second, the test verifies that safety related systems, which are normally idle, will function as intended when power is applied to the motor for any reason.

Coastdown tests are performed on those systems which normally have flow and whose flow decay is important to reactor safety. For example, the reactor coolant system must be operating in order to operate the reactor. If power is lost to reactor coolant pumps, safety feature actuation systems shut down the reactor. Should this occur, the coastdown flow of reactor coolant provides cooling which is additional to other safety cooling systems.

Coastdown tests are performed by measuring flow decay from time of interrupting power to the pumps to time of zero flow. Chart recorders are connected to the flow indication circuitry to plot flow versus time. A signal from an auxilliary contact on the pump switchgear can be patched to the chart recorder to give indication of the time of opening the switchgear. A backup measurement may be obtained from either pump head or pump speed. Decay of head or speed can be used for calculating flow decay or comparing the data with special pump performance curves which have been established for this purpose.

Coastdown tests serve the purpose of providing actual data for engineering's use in calculating reactor safety margins under postulated accident conditions.

System Tests

System tests verify that system functional design features are met. With respect to pumps, system pressure and flow requirements are typically tested in conjunction

with individual pump tests. That is, the individual pump capacity and head features are typically tested with the entire system. Other requirements for pumps which involve separate system testing pertain to automatic controls of the pump's operation.

Automatic controls associated with pump operation are typically of two varieties. One is a stop-start function and the other is a variable flow function.

Stop-Start System Tests

Certain pumping systems, such as core spray, containment spray, and waste collecting systems, are normally idle. Such systems are automatically started upon a control system demand. For example, containment pressure and temperature might be sensed and if either exceeds limits, a command is given to automatically start the containment spray pumps. In all such systems, instrumentation and control (I & C) components and circuitry are used to (1) sense the parameters of concern, (2) compare measured values against set points, and (3) initiate either start or stop signals to the pumps being controlled by that I & C system whenever measured values exceed set points. A simplified block diagram illustrating an automatic start-stop control system is provided by Figure 30-2-6.

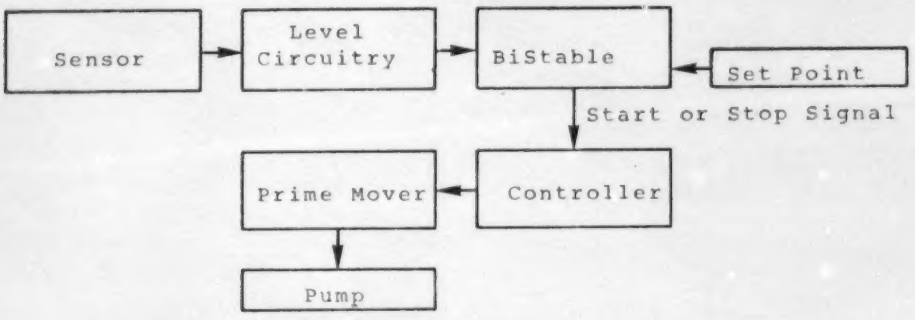

Figure 30-2-6. Block Diagram of Start-Stop Control Function

Tests of start-stop control systems verify that the pump starts or stops at the specified set point for each parameter of concern. Dependent upon the specific systems, one or more parameters may actuate the pump either as individual parameters or as the collective values of the parameters. The systems test simulates each parameter and determines if the pump starts or stops at each designated set point or combination of set points. Such tests require connection of hoses from pump discharge to a collection tank whenever it is undesirable to operate the fluid system. For example, testing of containment spray pumps would collect pump discharge because equipment within containment could be damaged by the spray.

Variable Flow System Tests

A few pumping systems are continuously operating but at various values of flow. For example, main feed water pumps are typically variable speed centrifugal pumps whose speed at any time is dependent on parameters such as steam generator water level. In this case, changes in water level result in a signal to the throttle valve controls of the feed pump turbine which adjusts turbine speed as necessary. Variable speed control systems (1) monitor designated parameters, (2) measure the value of the parameters, and (3) provide a continuous signal which is proportional to the value of the designated parameter. The continuous signal regulator pump speed either directly or inversely proportional to the values of the parameters. The simplified block diagram in Figure 30-2-7 illustrates a variable speed control function.

Tests of variable speed pumps simulate various levels of the designated parameters and determines if pump speed is properly regulated by the control systems. Pump speed may be indicated by flow or by revolutions per minute.

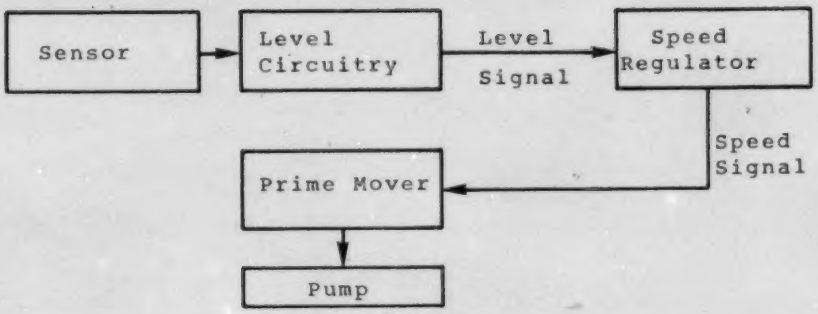

Figure 30-2-7. Block Diagram of Variable Speed Control Function

Pump speed at various values of designated parameters is recorded and compared with either a curve or table which provides design values. Level circuitry and the speed regulator are adjusted as necessary to obtain pump speed variations with parameter changes which match the design values within specified limits.

FUNCTIONAL TEST PROCEDURES

General Description

A test procedure is prepared and approved for use for each functional test to be performed. Each test procedure is sufficiently detailed for a qualified individual to perform the test without direct supervision. In addition, the procedure identifies witness and hold points where the Quality Control Department has elected to witness portions of the test or inspect designated test conditions. Test procedures receive independent review and approval prior to use and they provide for the recording of test data on the procedure. The completed procedure serves as the record of the test and provides test data for analysis and evaluation to determine acceptability of test results.

Format

The exact format of a test procedure varies somewhat from plant to plant. Nonetheless, all have in common seven sections. These are (1) title, number and revision, (2) test objectives, (3) test equipment, (4) limitations, (5) prerequisites, (6) procedure, notes and cautions, and (7) acceptance criteria.

- Title, number, and revision - The title names the test and the component or system to be tested. The number is typically an arbitrary number assigned by the owner. Each test procedure is given a unique number to permit easy reference to the procedure. The revision level is indicated by ascending numerical numbers or alpha designators or by date of approval. An example of title, number and revision is "Reactor Coolant Flow Test Procedure, TP0200.11.2" where TP = test procedure, 0200.11 = assigned number

and .2 = revision 2.

- Test objectives - Test objectives are stated in terms of the functional design features which will be tested by the procedure. A given procedure may test any number of functional design features provided the test is manageable within the necessary prerequisites.
- Test equipment - Test procedures require the use of installed measuring and test equipment as much as possible. When additional measuring and test equipment is needed, the procedure lists the specific typd of equipment which will be necessary. Examples include ammeters, voltmeters, tachometers, chart recorders, and special fluid collection containers.
- Limitations - This section of the procedure lists limitations if any, which apply to the conduct of the entire test. Examples include the minimum temperature at which the test can be performed, temperature ranges to be observed at all times during the test, and prohibitions on simultaneously starting pumps from a common power source.
- Prerequisites - This section lists all the conditions which must be established prior to commencing the test. Examples include filling and venting of the system, availability of pumping power, operability of pumping power, operability of instrumentation and control systems, safety tagging of switches and valves which must not be operated except as required by the test procedure, and isolation of interconnections which are not to be tested by the procedure.
- Procedure, notes, and cautions - This section provides sequential, step-by-step instructions for conducting the tests. The first step is typically to verify that each prerequisite and limitation has been

satisfied. Succeeding steps provide sequential action for conducting the test, recording test results, and returning the system to a described condition. Notes may be added, as necessary, to provide information which assists the tester. For example: "Note: the flow readout in lb/hr must be converted to gpm". Cautions are added, as necessary, to alert the tester to adverse conditions which could occur if the component or system malfunctions. For example: "Caution: The next step starts the containment spray pump. If unusual noise or vibration is observed, immediately stop the pump and notify the test supervisor". It is good practice to place notes and cautions immediately prior to the procedural step to which they apply. In this manner, the tester is more likely to observe the note or caution prior to performing the step.

- Acceptance criteria - This portion of the procedure lists the specific functional behavior which should be exhibited by the pump or system as determined from design specifications. The actual test results are evaluated and compared with acceptance criteria to determine if the pump or system can be declared acceptable for reactor plant operation.

Test Data Analysis and Evaluation

Test data may require engineering analysis to determine the significance of the data in terms of functional design features. Such analysis and evaluation of test data is performed by the responsible engineering group to determine acceptability of the pump or system. The results of the data analysis and evaluation are recorded on the test procedure.

Records

The test procedure serves as the record. The tester signs each procedural step as it is completed and records test data at steps requiring data collection. The engineer who evaluates the test data signs each acceptance criterion as it is confirmed that the test data provides satisfactory evidence of meeting acceptance criteria. The test supervisor also typically signs the completed procedure to certify that the procedure has been followed and that test results are complete and accurate to the best of the supervisor's knowledge.

EXERCISES

The following exercises serve to reinforce the information presented in this module. Answer each of the following exercises and check your answers using the answer key provided following each set of exercises.

A. This set of exercises refers to the information on Centrifugal Pump Characteristics and Reciprocating Pump Characteristics.

1. Define the following characteristics of centrifugal pumps:
   a. pump capacity

   b. pump head

   c. output power

   d. brake horsepower

   e. pump efficiency

2. As the discharge valve is closed in a centrifugal pump system, head (increases, decreases) and capacity (increases, decreases).
3. Describe how cavitation is avoided in a centrifugal pump.

4. Which organization provides performance curves for centrifugal pumps.

5. Define the following characteristics of reciprocating positive displacement pump:
   a. capacity

b. displacement

c. slip

6. Describe the relationship between capacity and discharge pressure for a positive displacement pump operating at a constant speed.

7. Why should the discharge path of a reciprocating positive displacement pump not be closed if the pump is running?

Check your answers to these exercises on Centrifugal Pump Characteristics and Reciprocating Pump Characteristics:

1. a. Capacity is the volume of fluid per unit time delivered by the pump.
   b. Head is the net work done on a unit weight of fluid in passing from the suction to the discharge.
   c. Output power is the liquid horsepower delivered by the pump to the fluid.
   d. Brake horsepower is the horsepower delivered by the prime mover to the pump shaft.
   e. Efficiency is the ratio of output power to brake horsepower.
2. Head increases, capacity decreases.
3. Cavitation is avoided by maintaining a dynamic suction head greater than the required Net Positive Suction Head identified by the pump manufacturer.
4. The pump manufacturer.

5. a. Capacity is the volume of fluid delivered per unit time.
   b. Displacement is the calculated capacity.
   c. Slip is the capacity loss as a percentage of suction capacity.
6. Capacity is essentially constant regardless of discharge pressure because capacity is fixed by pump design. Discharge pressure equals that of the system receiving the discharge.
7. Closing the discharge path of an operating positive displacement pump results in a rapid rise in discharge pressure which may rupture the pump or discharge piping.

B. This set of exercises refers to the information on the Functional Tests of Pumps.

1. State two purposes of pump functional tests.

2. State the purpose of the following individual pump tests:

   a. direction of rotation

   b. vibration

   c. motor load versus time

   d. seal cooling

   e. flow and pressure characterisitcs

   f. start-stop system tests

   g. variable flow system tests

3. Briefly describe how the following tests are conducted.

   a. direction of rotation

   b. seal cooling

   c. acceleration tests

d. start-stop system tests

4. Given the following values measured in a water transfer system, calculate pump head:

Discharge measurements: P = 60 lb/in^2, Flow = 500 gpm, pressure gage elevation = 26 ft, pipe cross-sectional area = .181 ft^2, highest elevation = 52 ft.

Suction measurements: P = 10 lb/in^2, pressure gage elevation equals 8 ft, pipe cross-sectional area = .181 ft^2, water supply level = 22 ft.

Other Data: pump datum = 12 ft, specific weight of water = 62.2 lb/ft^3.

Check your answers to the exercises on the Functional Tests of Pumps:

1. Pump functional tests verify that (a) the pump functions are designed and (b) the system containing the pump functions as designed.

2. a. Direction of rotation tests verify that the installed prime mover rotates in the direction that the pump must operate.

b. Vibration tests verify that the pump operates under load without excessive vibration.

c. Motor load versus time tests verify that the pump motor operates continuously under load without overheating or drawing excessive current.

d. Seal cooling tests verify that with the pump operating under load and normal cooling provided the seal temperature limit is not exceeded.

e. Flow and pressure characteristics tests verify that pump performance in the system is consistent with performance curves provided by the manufacturer.

f. Start-stop system tests verify that the pump starts or stops at designated set points for the controlling parameters.

g. Variable flow system tests verify that pump flow varies with changes in controlling parameters as designed.

3. a. Direction of rotation tests are performed by disconnecting the motor to pump coupling, applying power to the motor and visually observing direction of rotation of motor shaft.

b. Seal cooling tests are performed by verifying normal seal cooling flow, operating the pump at full load for a designated time, and measuring either rise in cooling water temperature or temperature of seal housing.

c. Acceleration tests are performed by measuring the time from initial start of the pump until it is running at operating speed. Charting current, flow, or discharge pressure may be used for the measurement.

d. Start-stop system tests are performed by simulating the control parameters, increasing the simulated signal level, and observing the level at which the start or stop function occurs. Individual parameters or combinations of parameters may be simulated.

4. 163.81 feet

Solution:

a. Suction and discharge velocity heads are equal and subtract to zero.

b. Correction for discharge pressure gage reading is (26 ft - 12 ft) ÷ 2.307 = 6.07 lb/in^2.

c. Correction for suction pressure gage reading is (8 ft - 12 ft) ÷ 2.307 = -1.73 lb/in^2.

d. $$H = \frac{Pd \times 144}{w} + Zd - \frac{Ps \times 144}{w} + Zs$$

$$= \frac{66.07 \times 144}{62.2} + 40 - \frac{8.27 \times 144}{62.2} + 10$$

$$= 192.96 - 29.15$$

$$= 163.81$$

C. Pump Testing

1. Visit a power plant in your area and observe the periodic test of a pump (or pumps) used in one of the power plant systems.

2. Prepare a report on your visit following the format outlined in the Procedures section of this module.

3. Collect the pump data and testing results as listed in data tables 30-2-3 and 30-2-4 respectively.

MATERIALS

Materials are not required for this module.

PROCEDURES

1. Make arrangements with a power plant in your area to observe a periodic test of a pump (or pumps) used in one of the plant systems as requested in exercises C.1, C.2 and C.3.

2. Visit the plant and observe the pump testing.

3. Complete the enclosed data tables. Table 30-2-3 is for the pump characteristics and Table 30-2-3 is for stating the purpose and description of each of the pump tests performed.

4. Prepare a short report on your visit which includes the following information:
   a. Data
   b. Plant visited
   c. Type of pump tested
   d. Type of system in which the pump is used
   e. Pump characterisitcs
   f. Types of tests
   g. Purpose of tests
   h. Descriptions of tests
   i. Results of tests

DATA TABLE

As requested in the Procedures section of this module collect the following data on the pumps tested:

Table 30-2-3

Pump Characteristics

Pump Name	
Rated Flow (gpm)	
Pump Head (ft)	
Design Pressure (psig)	
Driver Power (HP)	
Speed (nominal) (rpm)	
Remarks	

Table 30-2-4

Pump Tests, Purposes and Descriptions

Test	Purpose	Description
Direction or Rotation		
Vibration		
Motor Load vs. Time		

Table 30-2-4 (Continued)

Pump Tests, Purposes and Descriptions

Test	Purpose	Description
Seal Leakage		
Seal Cooling		
Flow and Pressure Characteristics		
Acceleration		
Coastdown		

REFERENCE MATERIALS

NRC, Regulatory Guide 1.68, Initial Test Programs for Water-Cooled Nuclear Power Plants, U.S. Nuclear Regulatory Commission, 1978

ASME, ANSI N45.2.8, Supplementary Quality Assurance Requirements for Installation, Inspection, and Testing of Mechanical Equipment and Systems for the Construction Phase of Nuclear Power Plants, American Society of Mechanical Engineers, 1975

NRC, Regulatory Guide 1.116, Quality Assurance Requirements for Installation, Inspection, and Testing of Mechanical Equipment and Systems, U.S Nuclear Regulatory Commission, 1977

ASME, ANSI N45.2, Quality Assurance Program Requirements (Design and Construction), American Society of Mechanical Engineers, 1972

EEE, 338, IEEE Standard Criteria for the Periodic Testing of Nuclear Power Generating Station Safety Systems, The Institute of Electrical and Electronic Engineers,1974

IEEE 334, IEEE Standard for Type Tests of Continuous Duty Class IE Motors for Nuclear Power Generating Station, The Institute of Electrical and Electronic Engineers, 1974

I.J. Karassih, W.C. Krutzsch, W.H. Fraser, J.P. Messina, Pump Handbook, McGraw-Hill, 1976

TEST

A. Answer the following set of questions as either true or false.

____ 1. Centrifugal pump performance curves furnished by the pump manufacturer plot head, efficiency, brake horsepower and net positive suction head against capacity. These curves are furnished for each pump design and identify how that design should perform.

____ 2. Centrifugal pump functional tests verify that a pump performs in its system as predicted by the pump performance curves.

____ 3. Pump head of the centrifugal pump is the algebraic difference between the total discharge head and the minimum required NPSH for the pump.

____ 4. The total discharge head consists of the sum of the pressure head, velocity head, elevation head and the turbulence head of the pump.

____ 5. Pump head represents the net work done on a unit weight of fluid in passing from the suction to the discharge.

____ 6. Reciprocating positive displacement pumps have an essential constant capacity when operating at constant speed regardless of discharge pressure.

____ 7. The discharge pressure of the positive displacement pump is proportional to the pump head provided that laminar flow is monitored through the pump.

____ 8. The capacity of variable speed reciprocating pumps varies directly proportional to the speed.

____ 9. Tests of reciprocating and rotary pumps verify that capacity at a designated speed and discharge pressure always be within $\pm$ 2% of its nameplate data.

____ 10. Cavitation in centrifugal pumps is the formation of gas bubbles on the impeller which is permitted by suction pressure lower than the vapor pressure of the fluid.

____ 11. Cavitation in reciprocating pumps is the formation of gas at the fluid-piston surface interface.

____ 12. Cavitation in any pump is prevented by providing a total discharge head greater than the required net positive suction head.

____ 13. Pump functional tests serve to verify that both the pump and the system containing the pump function as required by design intent.

____ 14. Most pump tests are performed during preoperational testing and cold functional testing. For PWRs, certain pump tests are repeated during not functional testing.

____ 15. Individual pump tests typically consist of (1) direction of rotation tests, (2) vibration tests, (3) motor load versus time tests, (4) seal leakage tests, (5) seal cooling tests, (6) flow and pressure characteristics tests, and (7) acceleration and coastdown tests.

____ 16. Pump system functional tests can be classified as stop-start functions, reverse-flow functions and motor winding overcurrent functions.

____ 17. Systems which have automatic starting or stopping of pumps are tested by simulating the control parameters and comparing the parameter level at which start or stop occurs with the designated set point. One or more parameters may activate the function either individually or in combination.

____ 18. Systems which have automatic adjustment of pump speed are tested by simulating the control parameters and measuring the change in flow. Change in pump head or speed could also be measured.

____ 19. Each functional test is performed in accordance with a test procedure. As a minimum, test procedures consist of seven sections: (1) title, number, and revision, (2) date, (3) temperature, (4) operator experience, (5) prerequisites, (6) test location and (7) acceptance criteria.

____ 20. The test procedure normally serves as the test record. Each procedural step is signed as it is completed, test results are recorded on the procedure, and verification signatures confirm that acceptance criteria are met.

B. Answer the following questions as indicated.

1. Define the terms capacity, pump head, output power, brake horsepower, and pump efficiency as they relate to centrifugal pumps.

2. Define the terms capacity, displacement, and slip as they relate to reciprocating pumps.

3. Recognize typical performance curves for centrifugal pumps and relate pump operating conditions to the curves.

4. Define cavitation and describe how it is avoided.

5. Describe the interrelationships of capacity, discharge pressure, pump speed, and discharge throttle valve settings for a reciprocating positive displacement pump.

6. State the purpose of and briefly describe how to conduct any of the following individual pump tests:
   a. direction of rotation
   b. vibration
   c. motor load versus time
   d. seal leakage
   e. seal cooling
   f. flow and pressure characteristics
   g. acceleration
   h. coastdown